Cassini Reaction Wheel Bearing Drag Performance 1997–2013†

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†Lee, A.Y. and Wang, E.K., "Inflight Performance of Cassini Reaction Wheel Bearing Drag in 1997–2013," AIAA-2013-4631, Proceedings of the AIAA Guidance, Navigation, and Control Conference, Boston, Massachusetts, August 19–22, 2013.

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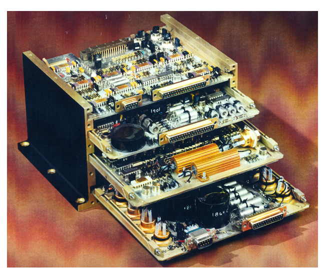
**With supports from Mimi Aung, Tom Burk, Chester Chu, Earl Maize, Peter Meakin, Joe Savino, and Julie Webster.

Scope

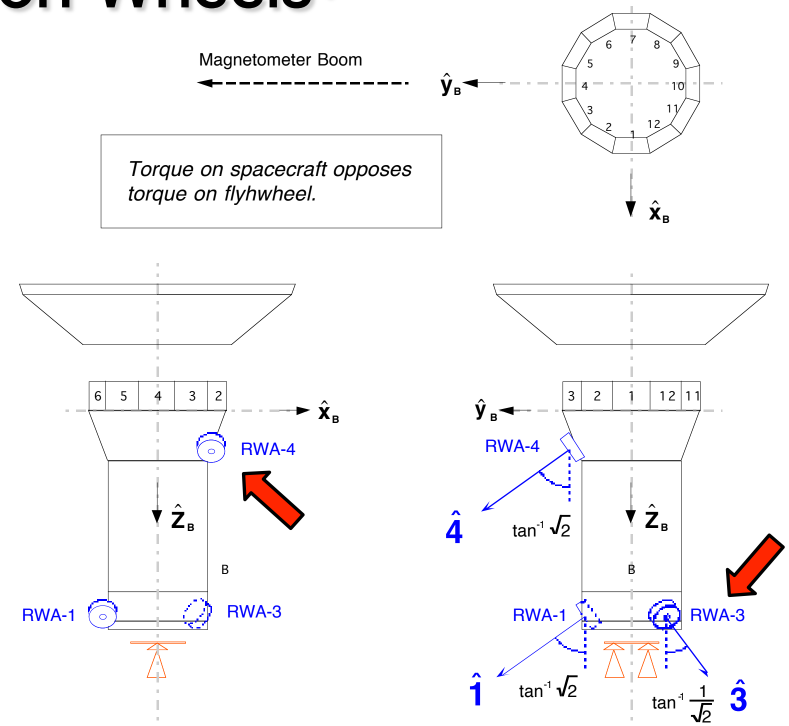
- The focus of this talk is on the management of spacecraft attitude control reaction wheels during the mission operations phase
- It will not cover various RWA design topics such as the sizings of wheel torque and momentum, configuration design, others
  - These topics are covered in, e.g., the JPL G&C System Engineering Class

Cassini Reaction Wheels†

- Reaction Wheel Assembly (RWA):
  - Three prime RWAs and an articulable RWA
  - They are used to achieve small attitude control error and good pointing stability
    - High resolution imaging and science data collection
    - Good Allan variance during three 40-day search for gravitational wave
    - S/C slew, mosaic, etc.



Cassini's RWA



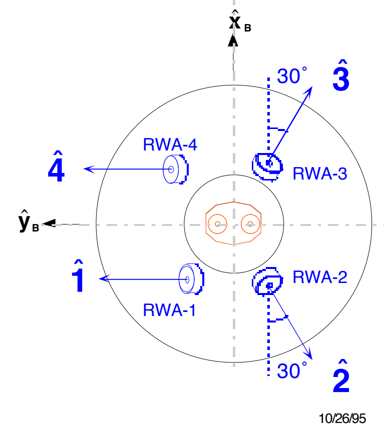
RWA Direction Cosines

$$
\begin{bmatrix} \hat{1} \\ \hat{2} \\ \hat{3} \end{bmatrix} = \begin{bmatrix} 0 & \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} \\ -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} \hat{x}_B \\ \hat{y}_B \\ \hat{z}_B \end{bmatrix}
$$

RWA4 is Redundant, Articulable

$\hat{4}$ can be aligned with $\hat{1}$ or $\hat{2}$ or $\hat{3}$

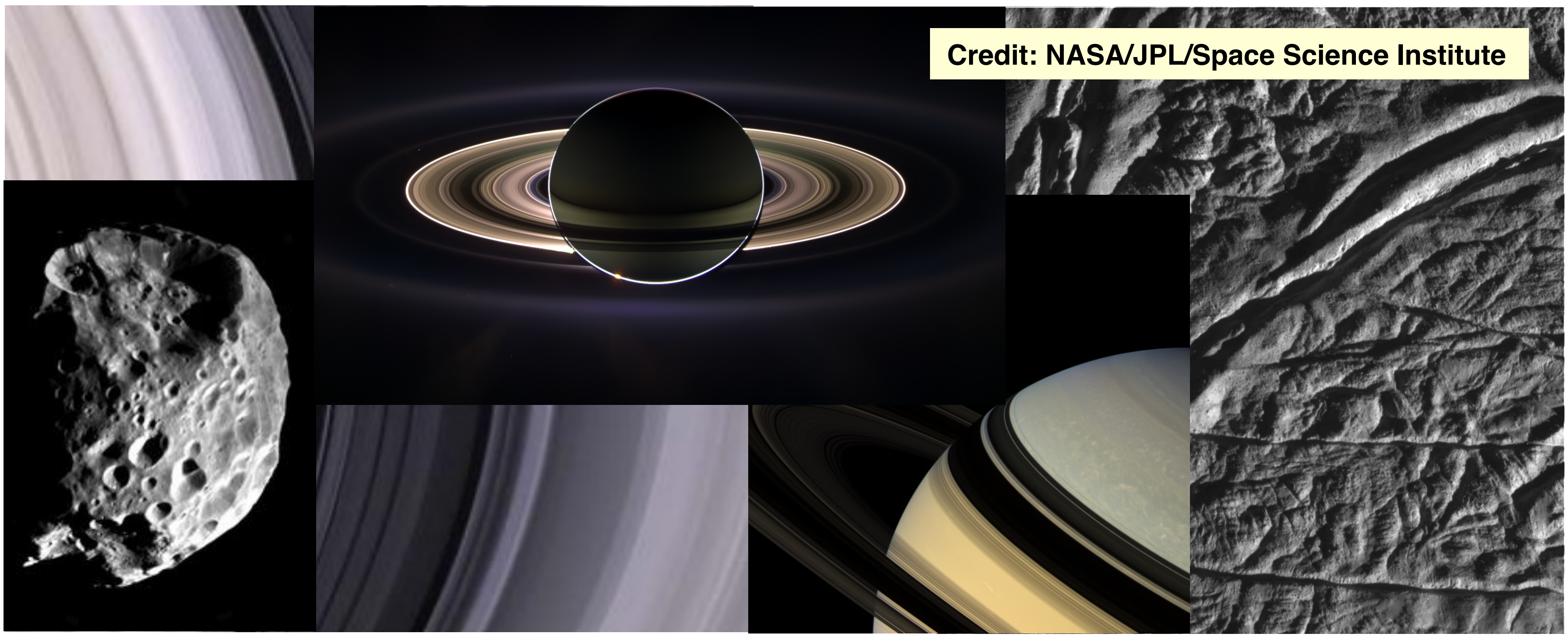
At Launch, $\hat{4}$ & $\hat{1}$ are aligned



†Macala, G. A., "Design of the Reaction Wheel Attitude Control System for the Cassini Spacecraft," AAS Paper 02-121, 27–30 January 2002.

Good Pointing Stability Performance†

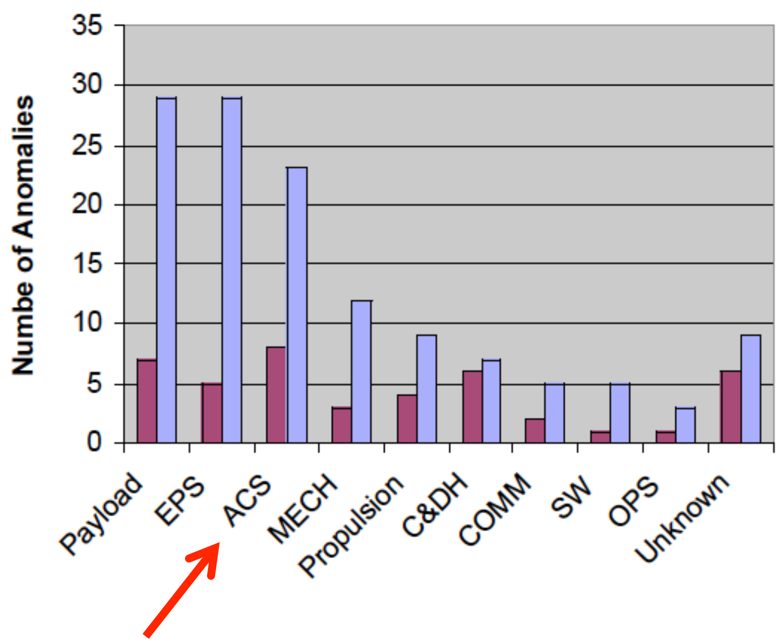
- Good pointing stability performance are confirmed by thousands of high-quality images returned by various science instruments

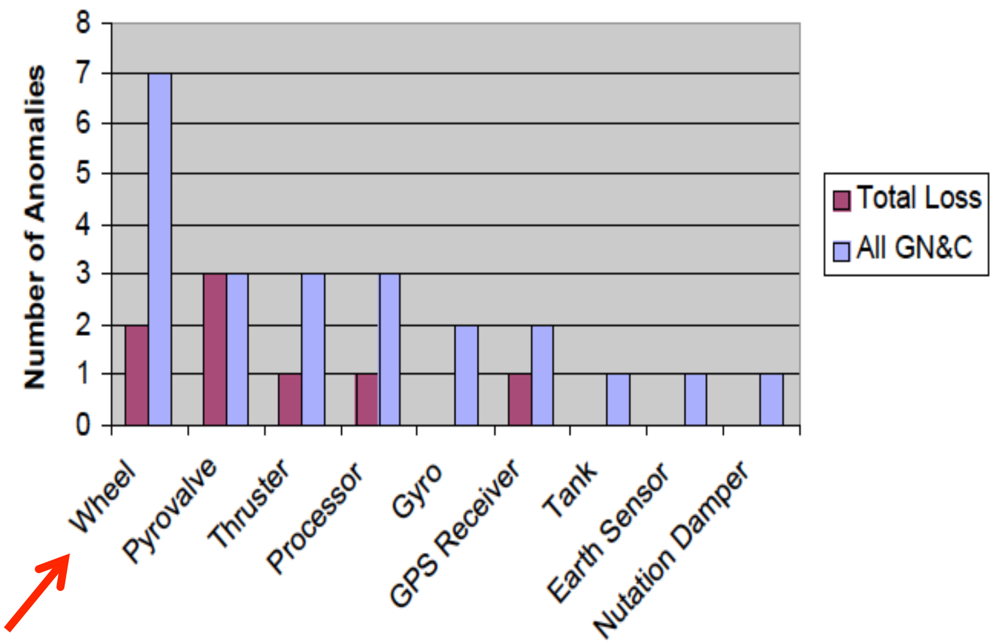


†Emily Pilinski and Lee, A.Y., "Pointing Stability Performance of the Cassini Spacecraft," Journal of Spacecraft and Rockets, Volume 46, No. 5, September-October, 2009, pp. 1007–1015.

Satellite GN&C Anomaly Trend†

- Anomalies recorded for satellites launched in1990–2001. It can be seen that Payload, EPS and ACS have a large contribution to reported anomalies
- GN&C anomalies vs. equipment type:
  - Pay attention to reaction wheels





†Robertson, B. and Stoneking, E., "Satellite GN&C Anomaly Trend," Paper AAS 03-071, 26th Annual AAS Guidance and Control Conference, Breckenridge, Colorado, 5–9 February 2003.

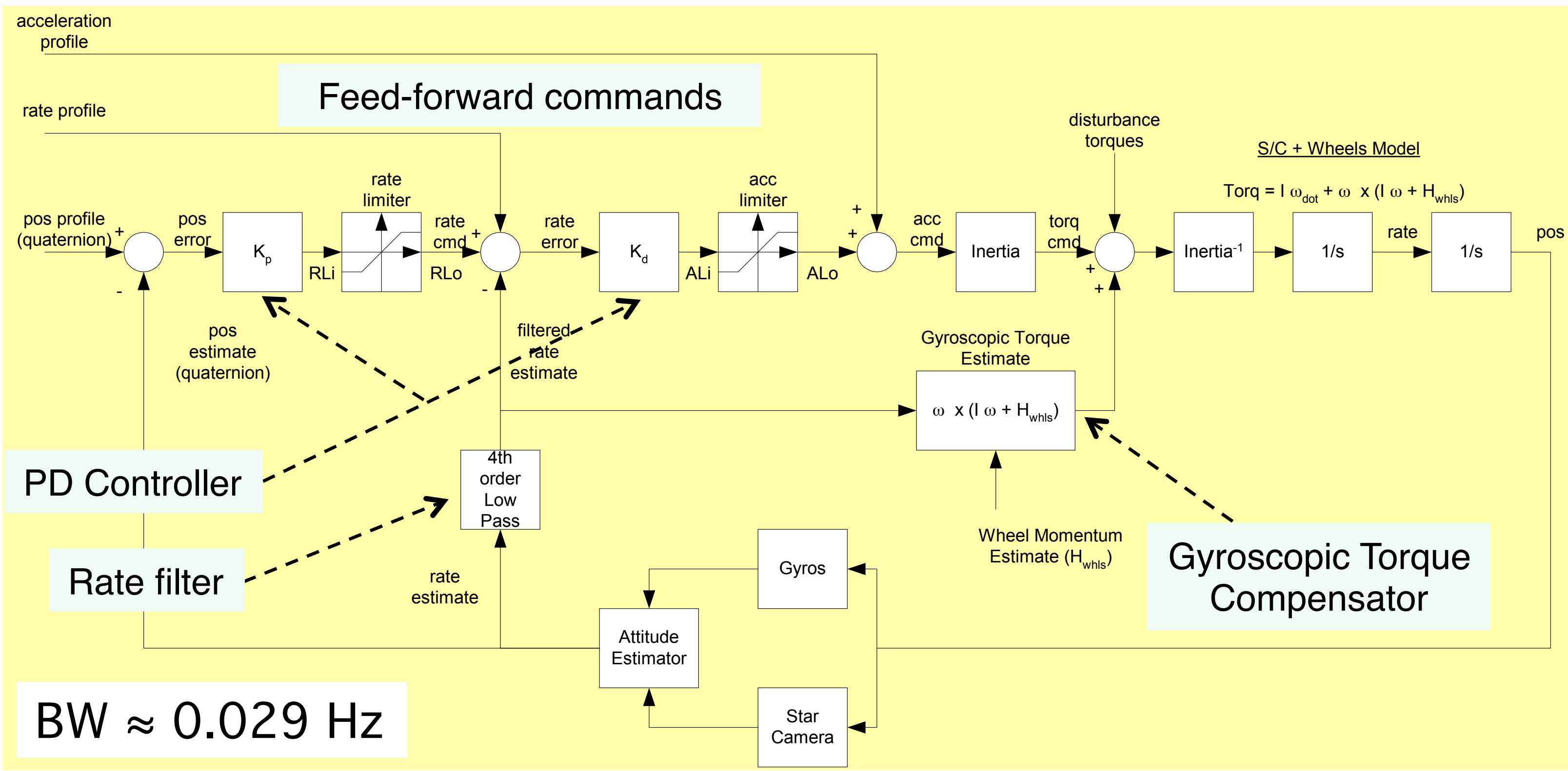
Spacecraft RWA Bearing-related Anomalies

Spacecraft (Launch Year)	RWA Bearing Anomalies/Year
IntelSat IV (1971)	High drag torque (1971)
GPS-5 (1978), GPS-6 (1983), GPS-14 (1989), GPS-18 (1990), GPS-20 (1990)	Degraded bearing system (various)
SAMPEX (1992)	Root cause of the wheel failure is hard to determine. However, wheel failure event was accompanied by elevated temperature (2007)
GOES-9 (1995)	Two wheels with Cage instability like symptoms. Total loss in 1998.
RadarSat-1 (1995)	Two wheels failed due to elevated drag (1999, 2002), Hybrid
EchoStar V (1999)	Degraded bearing system (2001, 2004, 2007), Hybrid
FUSE (1999)	Two permanent drag-related RWA failures (Nov. and Dec, 2001). Hybrid using 2 RWA and magnetic torque rods. Third failure in 2004
XMM-Newton (1999)	Degraded bearing system with cage instability problem in 2008-2011
TIMED (2001)	Degraded bearing system (2007). For hybrid controller, see Ref. 1
QuickSCAT (2001)	Low-rpm operations triggered RWA problem of 1 (of 4) RWA in 2001
Mars Odyssey (2001)	Degraded bearing system (2012, and 2013)
Hayabusa (2003)	Two permanent drag-related RWA failures (July and October, 2005). Hybrid using the remaining wheel and thrusters. See Ref. 2
Rosetta (2004)	Bearings of RWA-B and RWA-C have large drag spikes (2009-ongoing)
Dawn (2007)	Two RWA anomalies in 2010 and 2012. For hybrid controller, see Ref. 3
Kepler (2009)	Degraded bearing system (2012, 2013). Hybrid is being considered

1. Dellinger, W.F., and Shapiro, H.S., “Attitude Control on Two Wheels and No Gyros – The Past, Present, and Future of the TIMED Spacecraft,” AIAA/AAS Astrodynamics Specialist Conference, AIAA, Washington, DC, 2008.
2. Kuninaka, H. and Kawaguchi, J., “Deep Space Flight of Hayabusa Asteroid Explorer,” Proceedings of SPIE, Vol. 6960, Paper 696,002, 2008.
3. Bruno, D., “Contingency Mixed Actuator Controller Implementation for the Dawn Asteroid Rendezvous Spacecraft,” Paper AIAA-2012-5289, AIAA Space 2012 Conference and Exposition, Pasadena, California, 11–13 September 2012.

Reaction Wheel Assembly Controller (RWAC) Design†

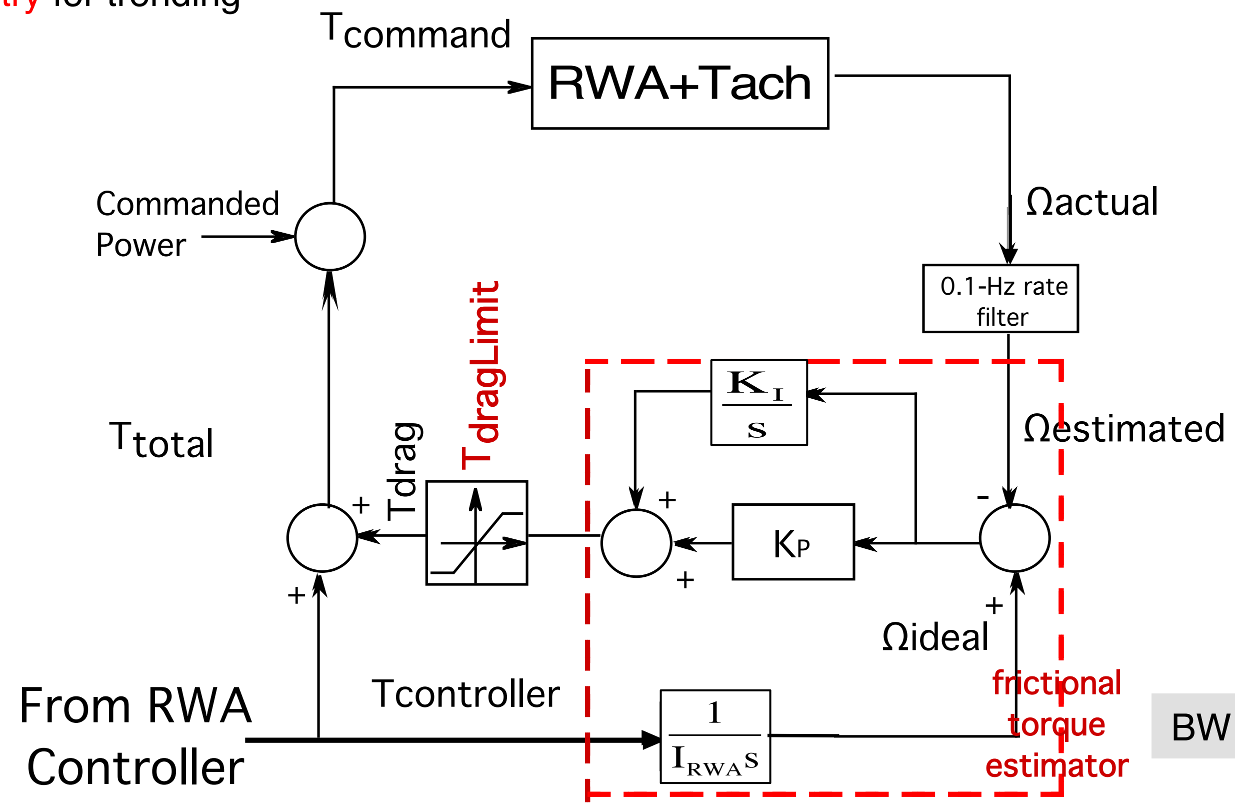
- The basic structure of the RWAC is a decoupled, three-axis, Proportional and Derivative (PD) controller
  - With rate and acceleration feed-forward commands
  - With compensation for gyroscopic torque



†Macala, G. A., “Design of the Reaction Wheel Attitude Control System for the Cassini Spacecraft,” AAS Paper 02-121, 27–30 January 2002.

Wheel Bearing Drag Estimation and Compensation†

- Flight software (FSW) has a PI estimator that estimates the RWA drag torque. The estimated torque is used:
  - To compensate the torque command from RWA controller
  - To feed a set of "Excessive Drag Torque" error monitors
  - To telemetry for trending



BW ≈ 0.01 Hz

†Meakin, P.C., "Cassini Attitude Control Fault Protection: Launch to End of Prime Mission Performance," Paper AIAA-2008-6809, Proceedings of the AIAA Guidance, Navigation, and Control Conference, Honolulu, Hawaii, 18–21 August 2008.

Trending the RWA Bearing Drag Performance

- RWA Drag Torque Model:

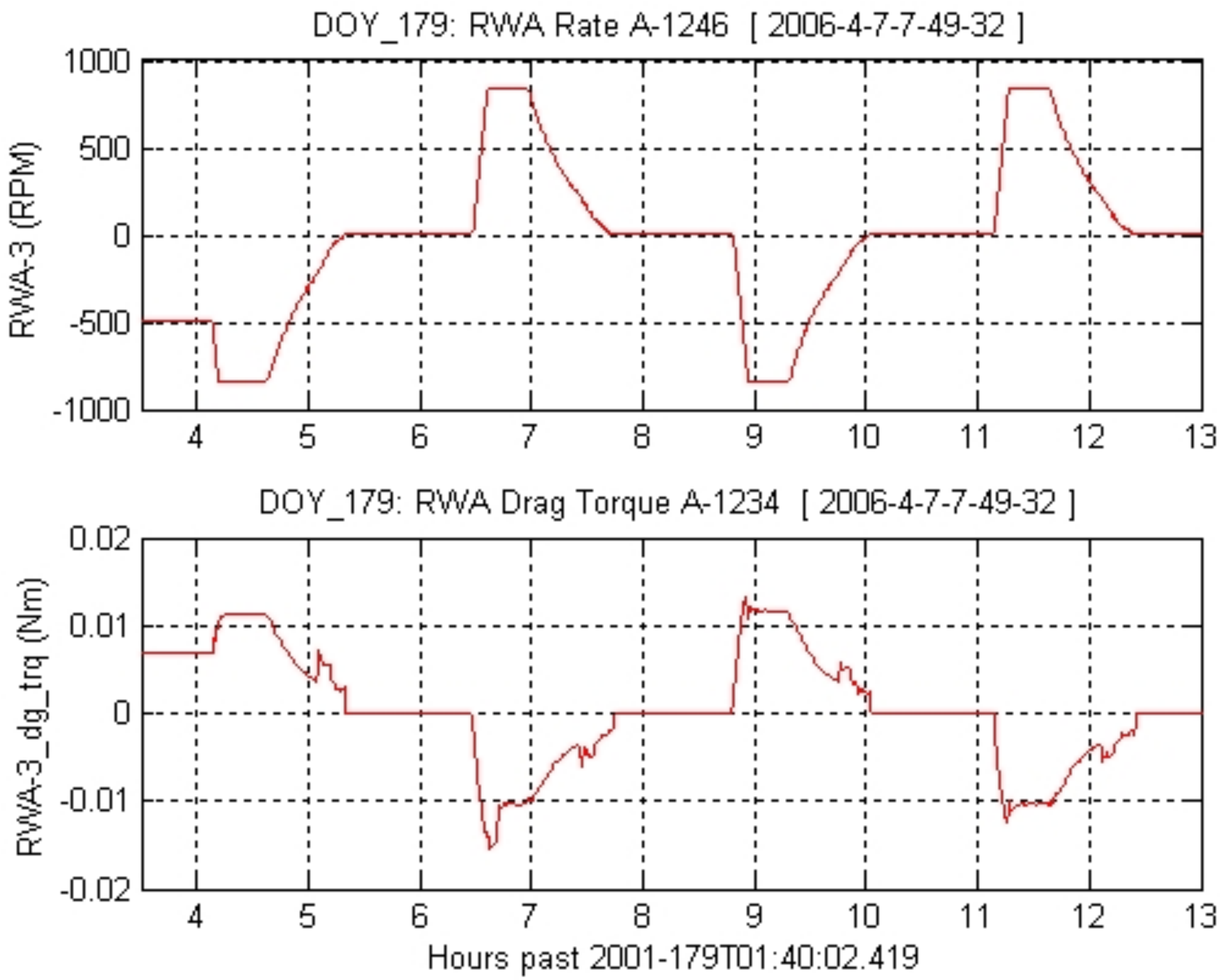
$$T_{drag} = -c \times \omega - T_{Dahl} \times \mathrm{sgn}(\omega)$$

- From an initial rate of Ω_0, RWA coast-down rate ω(t) is:

$$\omega(t) = -\frac{T_{Dahl}}{c}\mathrm{sgn}(\omega) + \{\Omega_0 + \frac{T_{Dahl}}{c}\mathrm{sgn}(\omega)\}e^{-\frac{t}{\tau}}$$

- Data from ±900 rpm coast-down tests are used to estimate the viscous coefficient and Dahl friction of the prime/backup wheels
  - Clockwise (CW) and CCW values are determined separately
  - Parameters are trended
  - Values are used in simulation test beds
  - Values are also used in other ground software (RBOT, see the following pages)

Representative RWA Bearing Coast-down Test Profile



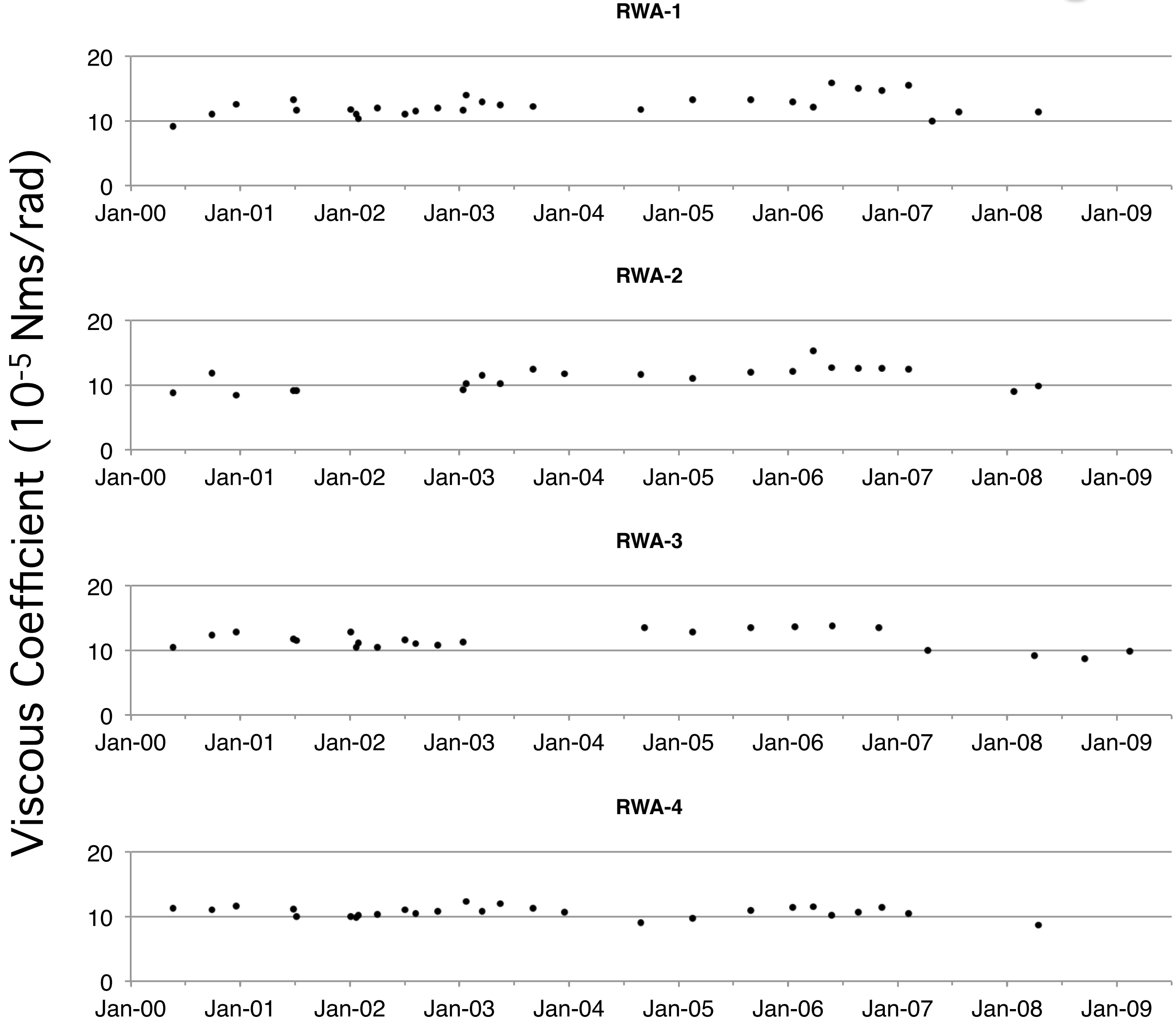
Cassini Inflight RWA Bearing Drag Torque Tests

- From 1999-DOY-025 to 2009-DOY-291 (3,916 days), there were 44 coast-down tests performed for the prime RWA. Once every 89 days
- The hydrazine cost of a coast-down test depends on both the initial RWA spin rate of the test and the possible occurrences of drag spikes during the test
  - The average per-test hydrazine cost of the ±900 rpm tests was about 21 g
  - That for the ±600 rpm was about 13 g
  - These tests weren't cheap!

Table 1. Cassini RWA Drag Torque Characterization Tests

<table>
<tr><th>Year</th><th>Days of Year for RWA-124 Tests</th><th>Days of Year for RWA-3 Tests</th><th>Comments</th></tr>
<tr><td>1999</td><td colspan="2">025, 078, 139, 249, 353</td><td rowspan="3">RWA-1234 coast-down initial tests with rates used: ±836 and ±418 rpm</td></tr>
<tr><td>2000</td><td colspan="2">143, 272, 354</td></tr>
<tr><td>2001</td><td colspan="2">179, 190</td></tr>
<tr><td>2002</td><td colspan="2">005, 024, 032, 094, 187, 221, 295</td><td>RWA-1234 coast-down tests with initial rates: ±900 rpm.</td></tr>
<tr><td>2003</td><td colspan="2">014, 026, 079, 140, 250, 354</td><td>First test was performed with [-739, -537, -547] rpm only for RWA-123. All others were performed with initial rates of ±900 rpm.</td></tr>
<tr><td>2004</td><td>137, 139, 243</td><td>138, 256</td><td rowspan="6">RWA-124 coast-down tests with initial rates of ±900 rpm.
RWA-3 coast-down tests were performed separately with initial rates of ±600 rpm</td></tr>
<tr><td>2005</td><td>052, 244</td><td>052, 244</td></tr>
<tr><td>2006</td><td>021, 089, 149, 238, 319</td><td>026, 153, 307</td></tr>
<tr><td>2007</td><td>042, 121, 210, 299</td><td>106, 301</td></tr>
<tr><td>2008</td><td>029, 110, 170, 288</td><td>097, 267</td></tr>
<tr><td>2009</td><td>017, 115, 291 (last test)</td><td>051</td></tr>
</table>

Trends of Cassini RWA-1234 Bearing Viscous Coeff.



RWA	Pre-launch Mean Viscous Coeff† (10^{-5} Nms/rad)
1	11.4
2	9.9
3	9.9
4	9.9

†At 25±1 ˚C

Monitoring of Drag Torque Using Flight Telemetry

- No RWA spin-down tests since 2009
- Drag torque trending now uses only telemetry from science ops
- <u>RWA Trending Strategy:</u>
  - **During 3 months each RWA spends enough time spinning at different rates to give a snapshot of typical drag torque levels**
  - S/C slews frequently between attitudes, thus RWA spin-rates always changing
  - Every 3 months divide RWA telemetry into bins of time spent at various spin-rates (e.g. 250 rpm - 350 rpm is one bin)
  - Over 3 months each RWA spends ~20-200 hours in each data bin between 300 rpm and 1500 rpm

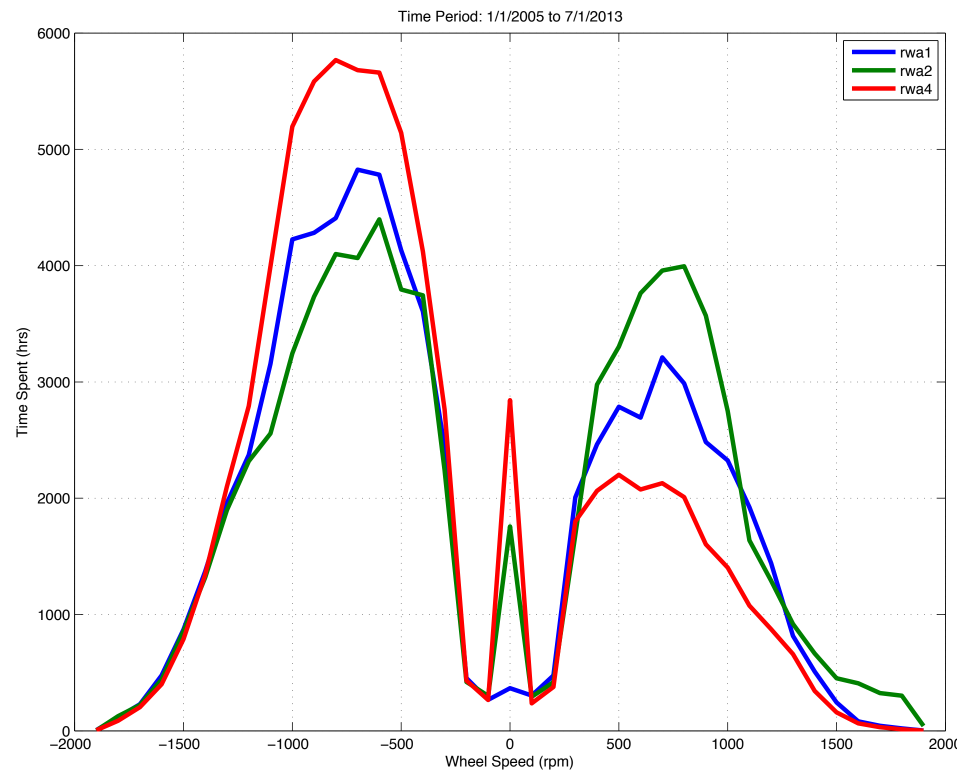
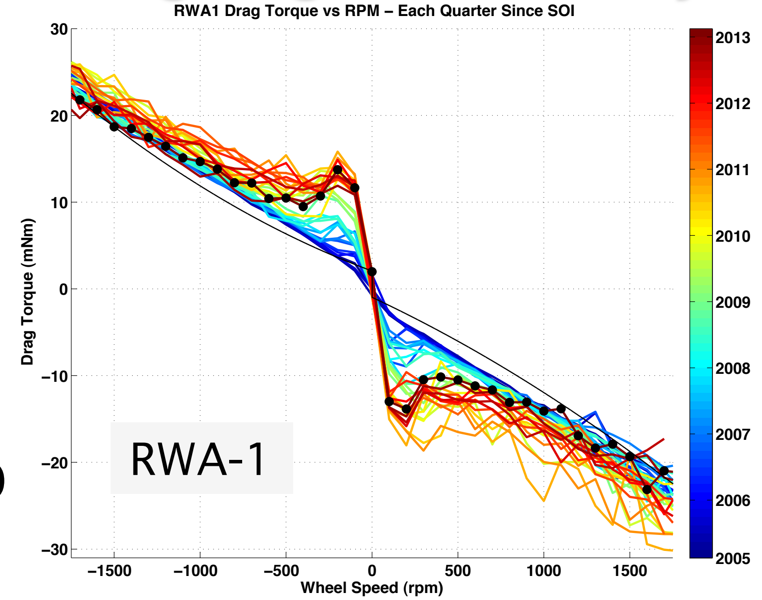
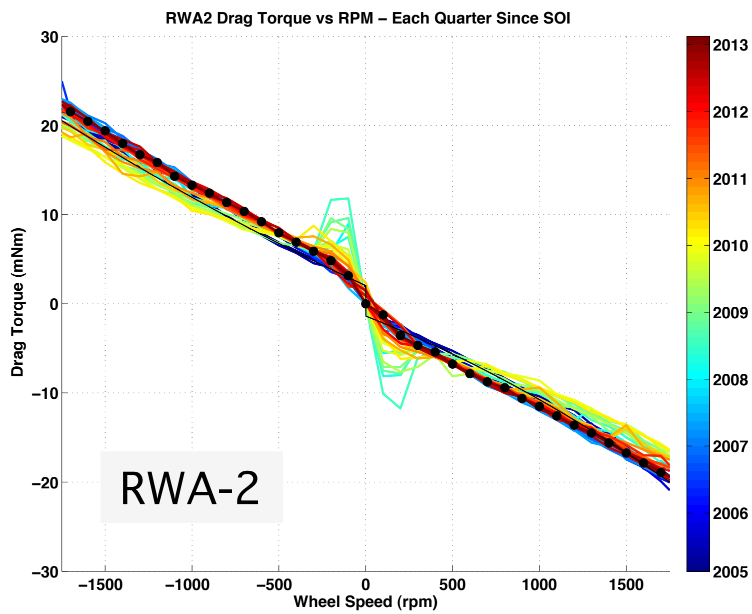


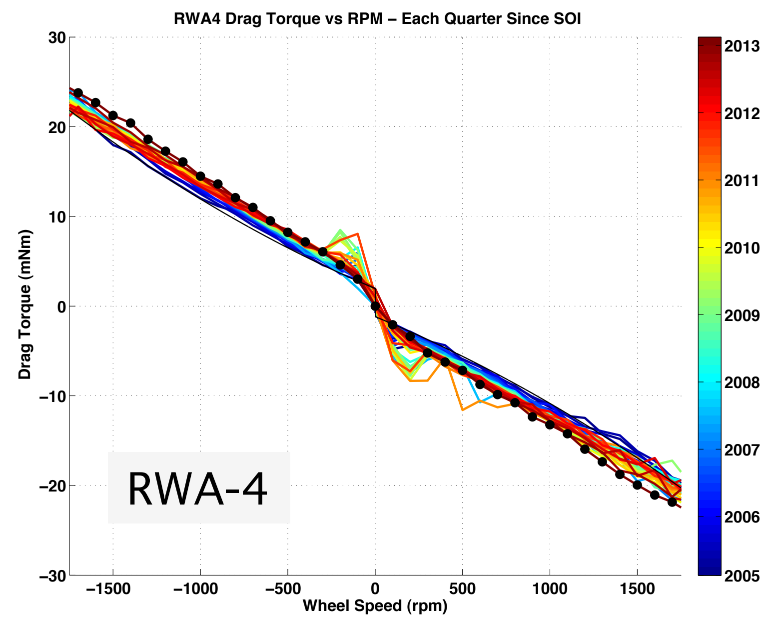
Figure: Total time each RWA spent at various spin rates between 2005 and 2013

Monitoring of Drag Torque Using Flight Telemetry

- <u>RWA Drag Torque Trending:</u>
  - Bin drag torque telemetry based on time spent in 100 rpm wide spin-rate bins
  - Find median RWA drag torque for each bin
  - Plot median drag torque levels from this quarter with historical results to see trends
- Similar approach is used by ESA SOHO mission control team

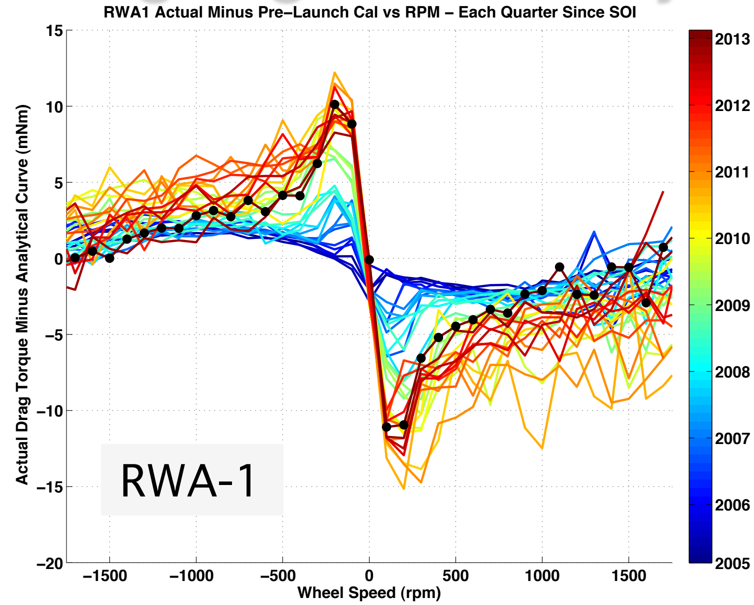


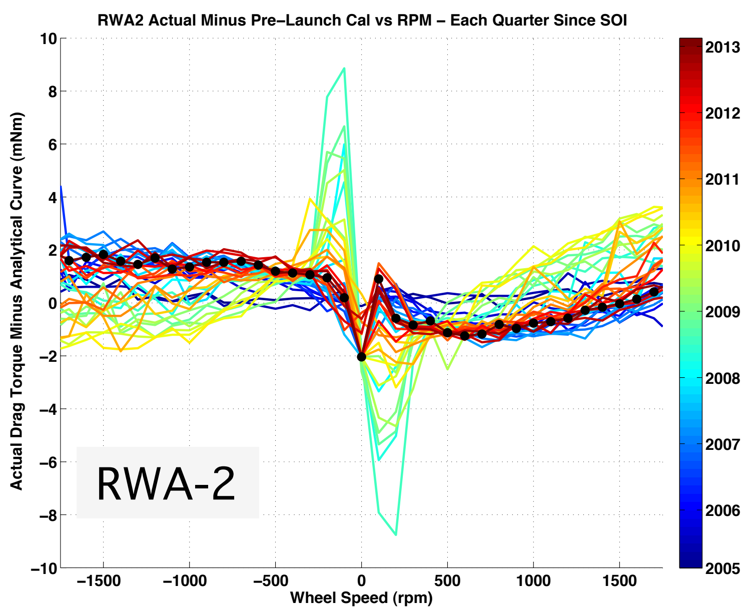


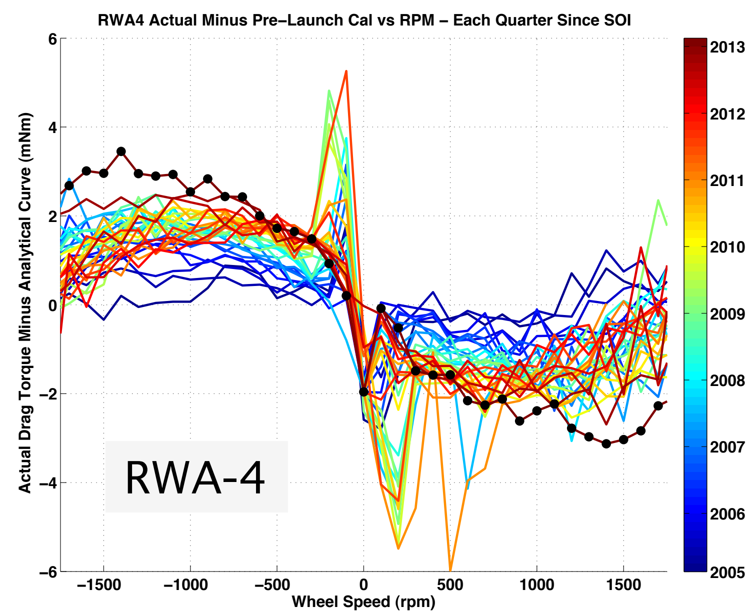


Monitoring of Drag Torque Using Flight Telemetry

- <u>RWA Drag Torque Trending:</u>
  - To aid visibility on plots the data is normalized
  - Normalized by subtracting a predicted drag torque curve based on pre-launch measurements

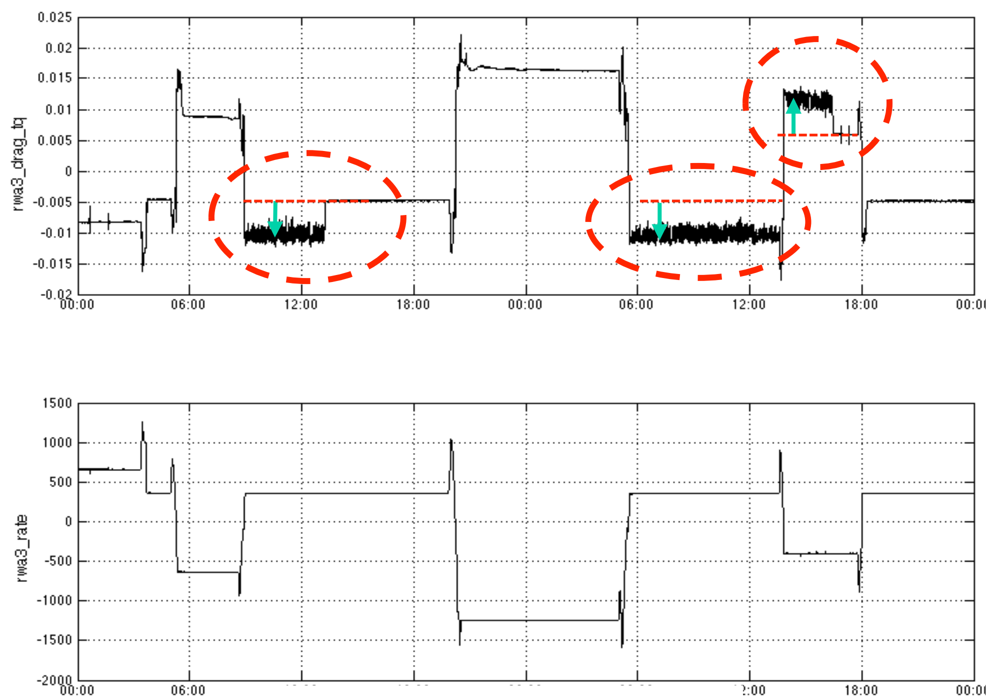






RWA-3 Anomalous Bearing Drag Observed in October 2002

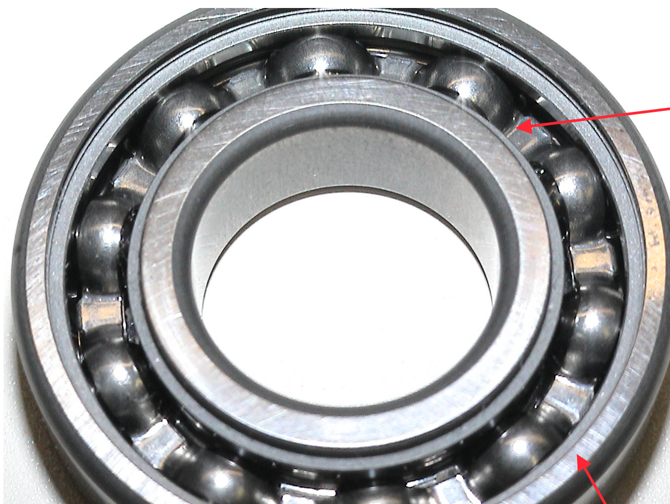
- Drag torque "steps" were observed on RWA-3 (2002, DOY 291–95)
  - Large frictional drag torque steps were observed:
    - Frequently triggered by a RWA spin rate reversals
    - Step size ≈ 5-6 mNm (20% of the peak drag)
    - Step duration ≈ 4-10 hrs
  - "Roughness" of steps is an order of magnitude larger than its nominal value



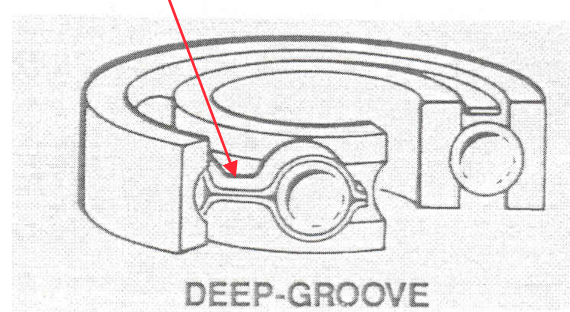
From 2002-292T00:00:00

Bearing Cage Instability

- Based on the following observed symptoms:
  - Large “step” increase in drag torque
  - Spontaneous drag torque step up and step down
  - “Noisy” drag torque
- Our diagnosis of the RWA-3 problem is: Bearing cage instability
  - It is independently confirmed by our wheel bearing consultants



Cage (retainer, separator)
Two-piece ribbon 430
corrosion-resistant steel



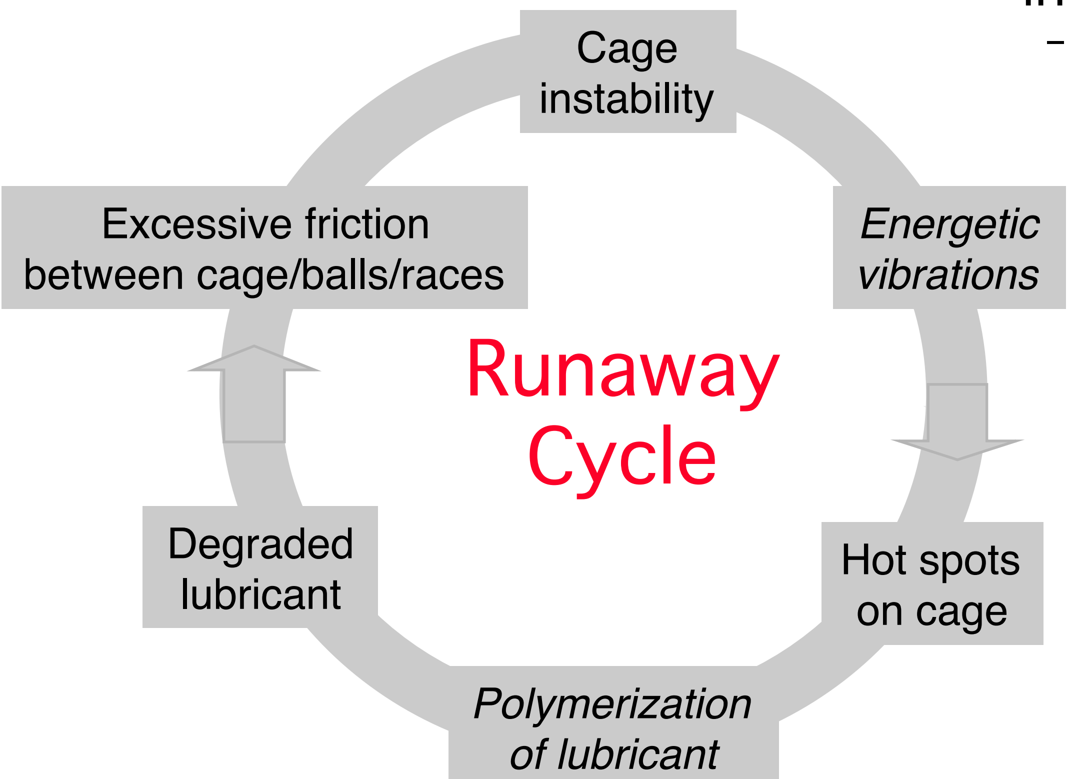
Both Inner and outer raceways, and balls are made of hardened 52100 alloy steel

A Comparison of Bearing C.I. Symptoms

Bearing CI Drag Characteristics	NASA Cassini-Huygens RWA-3		ESA XMM-Newton RWA-1
Years of anomaly	2002–3	2011	2008–11
Drag Torque Step size [mNm]	5–8	3–9	18–20
Drag Oscillation Frequency [mHz]	8–11	3–9	TBD
Roughness [mNm]	2–3	0.3–2.5	4–5
Individual duration [hour]	2–50	1–96	1–4
Abundance (hour with cage instability per hour RWA is powered on)	8.7%	19.3%	10–25%
Range of CW spin rate with CI [rpm]	+300 to +1000	+300 to +1500	+600 to +3000
Range of CCW spin rate with CI [rpm]	-1000 to -600	-1000 to -700	-3000 to -800

Likely Failure Mode

- Worrisome Cycle:

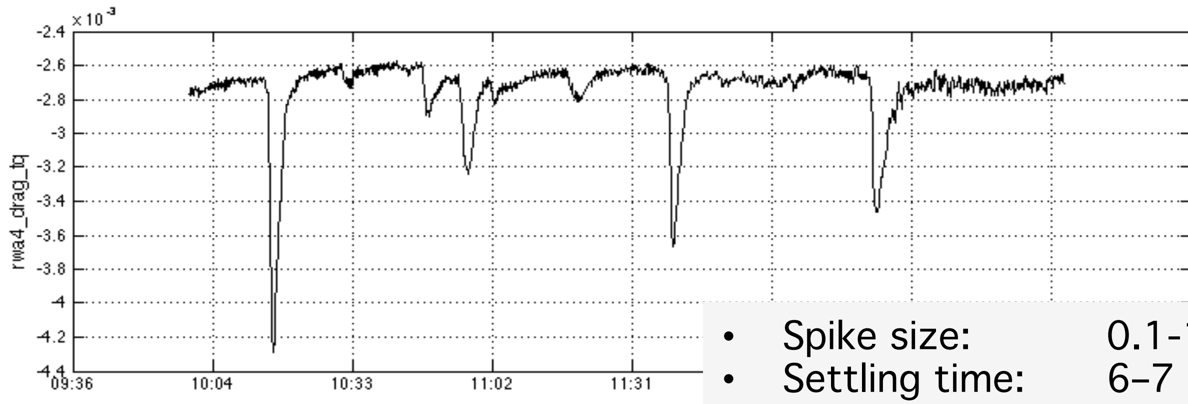


- Degraded cage structural integrity:
  - Large number of vibration cycles will weaken the metallic cage at places with stress concentration

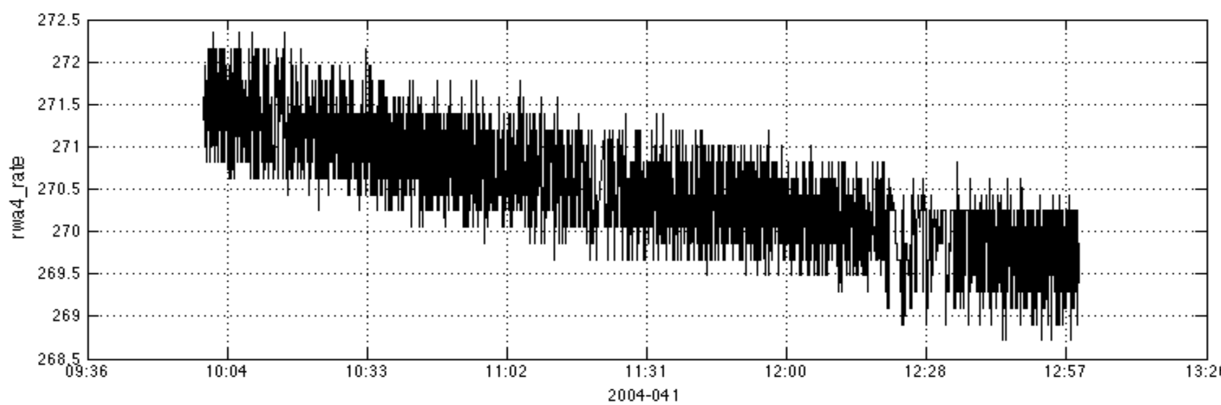
- RWA-3 drag was replaced by the backup RWA-4 in July 2003
  - After an 8-year rest, it was reused as a prime RWA (in 2011). But the cage instability symptoms returned and RWA-3 is made a backup RWA again

Anomalous Drag Torque Spikes

- “Spiky” drag torque occurred frequently on all wheels:
  - An example: RWA-4 at a near-constant spin rate of 271 rpm, 2000
  - The initial impulsive rise in drag torque is often time followed by either a rapid (several minutes) or gradual (several hours) exponential decay

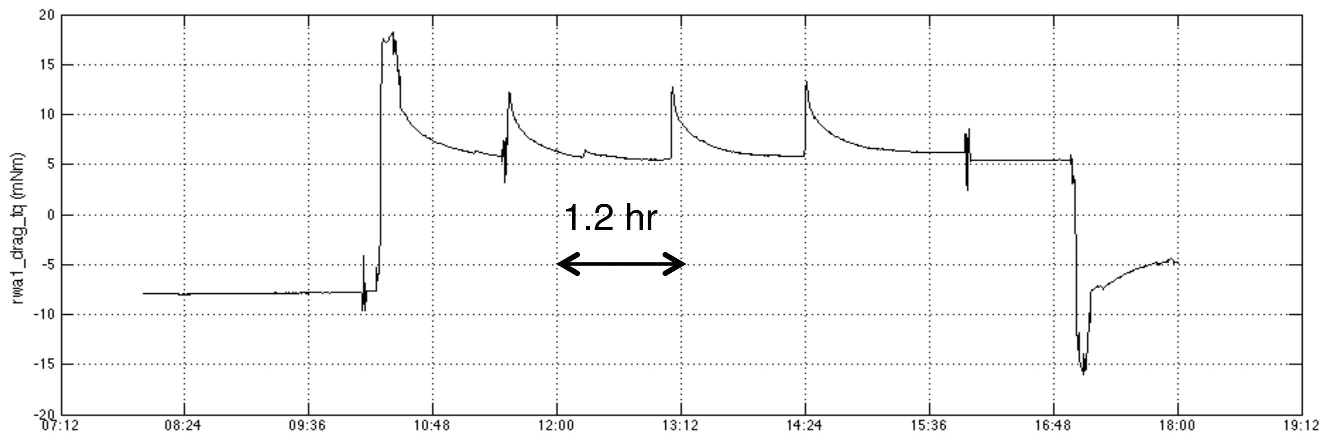


- Spike size: 0.1-1.5 mNm
- Settling time: 6–7 min.

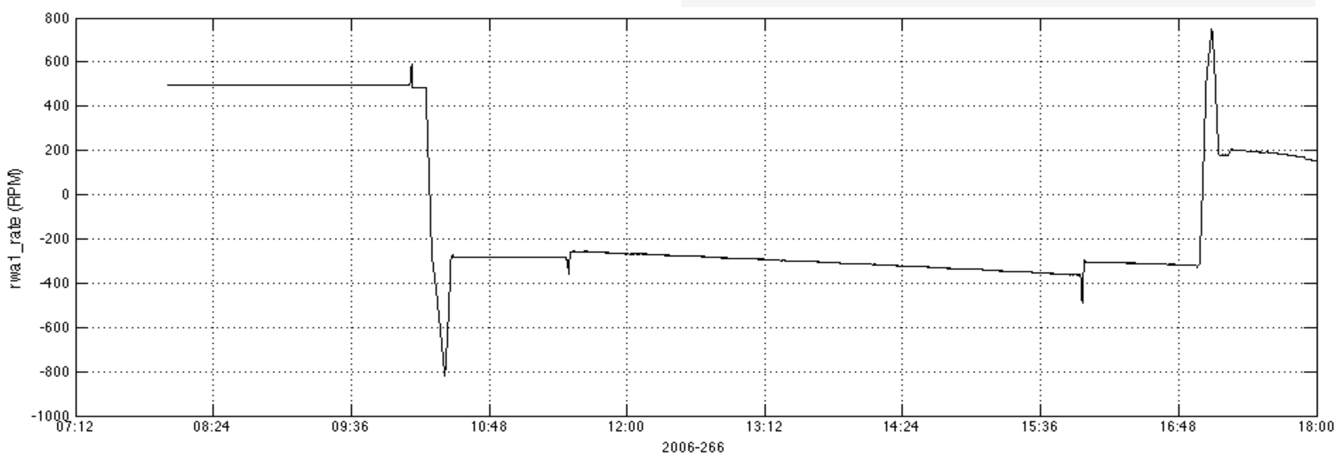


RWA Bearing Drag Torque Spikes (Long Settling Time)

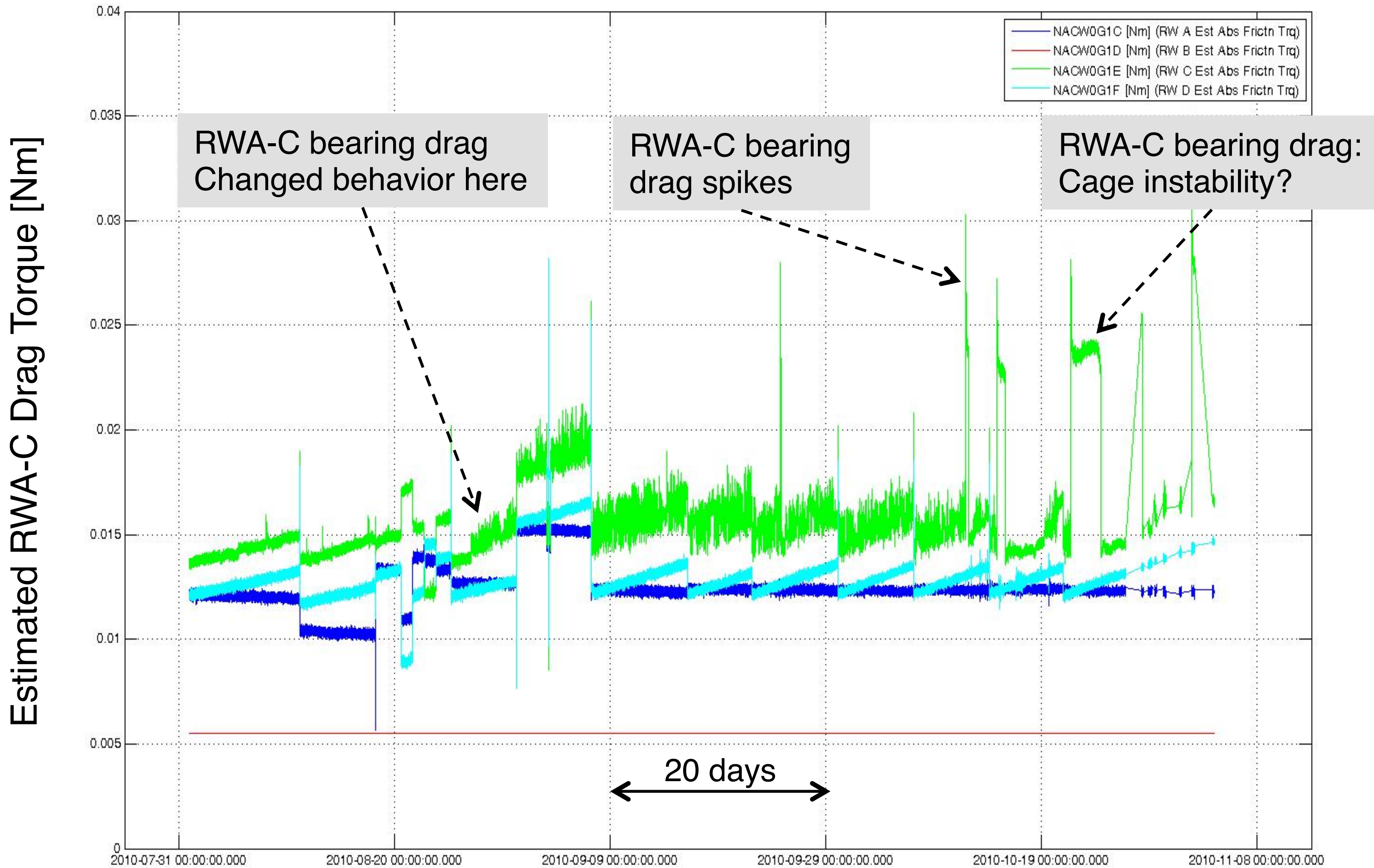
- An example: RWA-1 at a near constant spin rate of -250 rpm, 2004



- Spike Size: 6-7 mNm
- Settling time: 1.4–1.5 hr



Observed Bearing Drag Torque Spikes in ESA Rosetta RWA (2010)



Anomalous Drag Torque Spikes: Cause

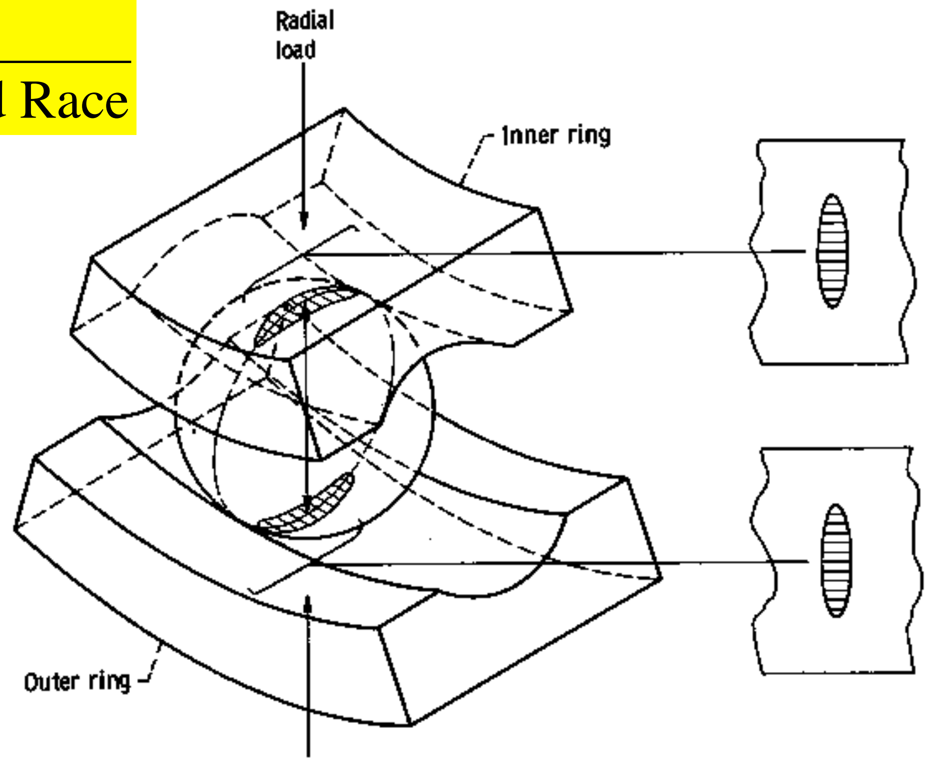
- Definitive cause is unknown. Our conjecture is it is an “oil jog” phenomenon
  - Small pockets of lubricant that collect outside of the normal ball/cage and ball/race contact areas
  - They can become entrained in the contact areas by a variety of processes
  - Bearings that suddenly encounter an addition of oil will show an abrupt increase in drag that will then dissipate by various processes
- If this conjecture is right, the observed spikes are actually a positive indication of the presence of useful oil in bearings
- Selected FSW fault protection-related monitors’ thresholds were raised to guard against accidental triggering of error monitor by these transient drag torque spikes[†]

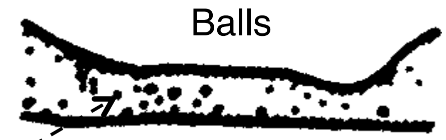
[†]Meakin, P.C., “Cassini Attitude Control Fault Protection: Launch to End of Prime Mission Performance,” Paper AIAA-2008-6809, Proceedings of the AIAA Guidance, Navigation, and Control Conference, Honolulu, Hawaii, 18–21 August 2008.

Stay Out Low-rpm Zone - Lambda Value

$$\lambda = \frac{\text{Lubricant Film Thickness}}{\text{Composite Roughness of Ball and Race}}$$

- Boundary Lubrication ($\lambda \leq 1$):
  - Metal-metal contacts promotes wear
  - Excessive heating promotes lubricant polymerization
  - Shorten bearing life
- EHL† condition ($\lambda > 1$):
  - Recommended for long life operations
  - Spin rates ≥300 rpm are needed to achieve $\lambda \geq 1$
- We use a tool *RBOT* to ascertain that RWA do not spend excessive time in the sub-EHL region





†EHL= Elasto Hydrodynamic Lubrication

RBOT Solves A Nonlinear Deterministic Wheel Bias Selection Problem

- Required spacecraft momentum is known from mission design
  - Per-axis S/C rate time histories
  - Attitude quaternion time histories

- Conservation of angular momentum in inertial frame

$$\vec{h}_o + \vec{h}_{ext} = \vec{h}_{sc} + \vec{h}_{rwa}$$

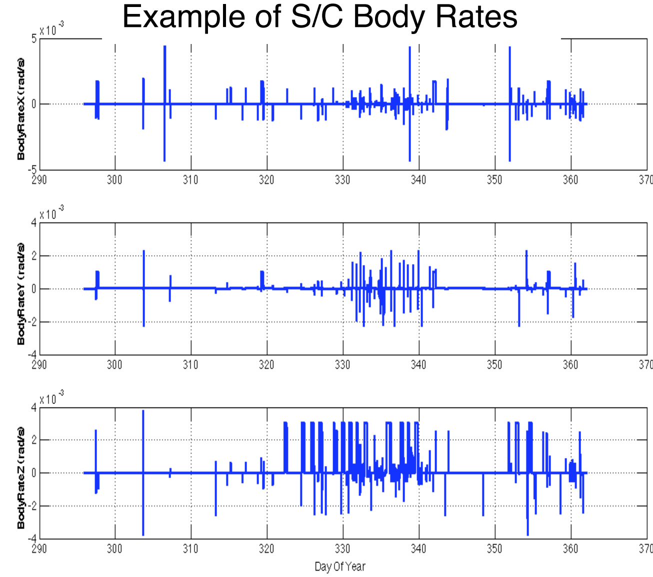
$$\vec{\omega}_{rwa} = \underbrace{I_{rwa}^{-1} C_i^{rwa} C_{rwa}^{io} I_{rwa}}_{[a_{i\text{-}th}]} \vec{\omega}_{bias} + \underbrace{I_{rwa}^{-1} C_i^{rwa} (-\vec{h}_{sc} + \vec{h}_{ext})}_{[b_{i\text{-}th}]}$$

  - Matrices [a] and [b] are time-varying constants computed using the known time histories of the S/C's attitude and rate

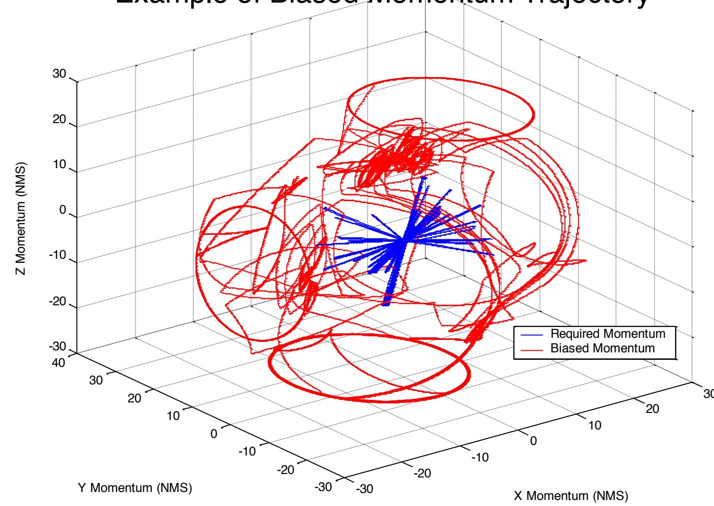
- Computational efficient formulation of wheel speed equation as a function of input wheel bias

$$\vec{\omega}_{rwa} = [\mathrm{a}]\vec{\omega}_{bias} + [\mathrm{b}]$$

Example of S/C Body Rates

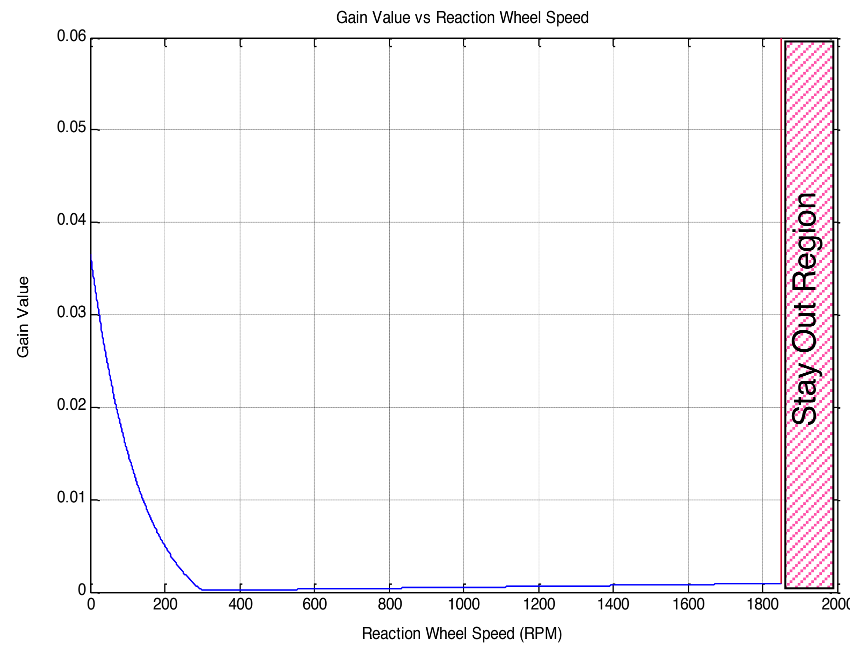


Example of Biased Momentum Trajectory



Cost Functional Penalizes Low RPM Speed Region

- Optimization parameter: cost index K_i assigned to reflect operational constraints
  - Lower bound of the recommended EHL speed range (±300 rpm) selected as the threshold for low-rpm penalty region
  - Exponentially increase penalty for “nearness” to zero RPM inside the low-rpm region
  - Limit maximum wheel speed to 1850 rpm to provide margins for modeling uncertainties
  - Weigh the cost index K_i for low RPM region at 3.6 times the high revolution region to account for relative consumption ratio



$$K_i = \frac{3.6 * X1}{\sum X1} + \frac{X2}{\sum X2}$$

$$X1 = \frac{(e^{-0.0075*\omega_1} - e^{-2.25})}{c^2 * 12000} \qquad \omega_1 = [0:300]$$

$$\omega_2 = [0:1850]$$

$$X2 = \frac{\omega_2}{c * 4e + 9} \qquad c = 60$$

RBOT Optimization: Search For Global Minimum

- Wheel speed profile model as a function of input wheel bias

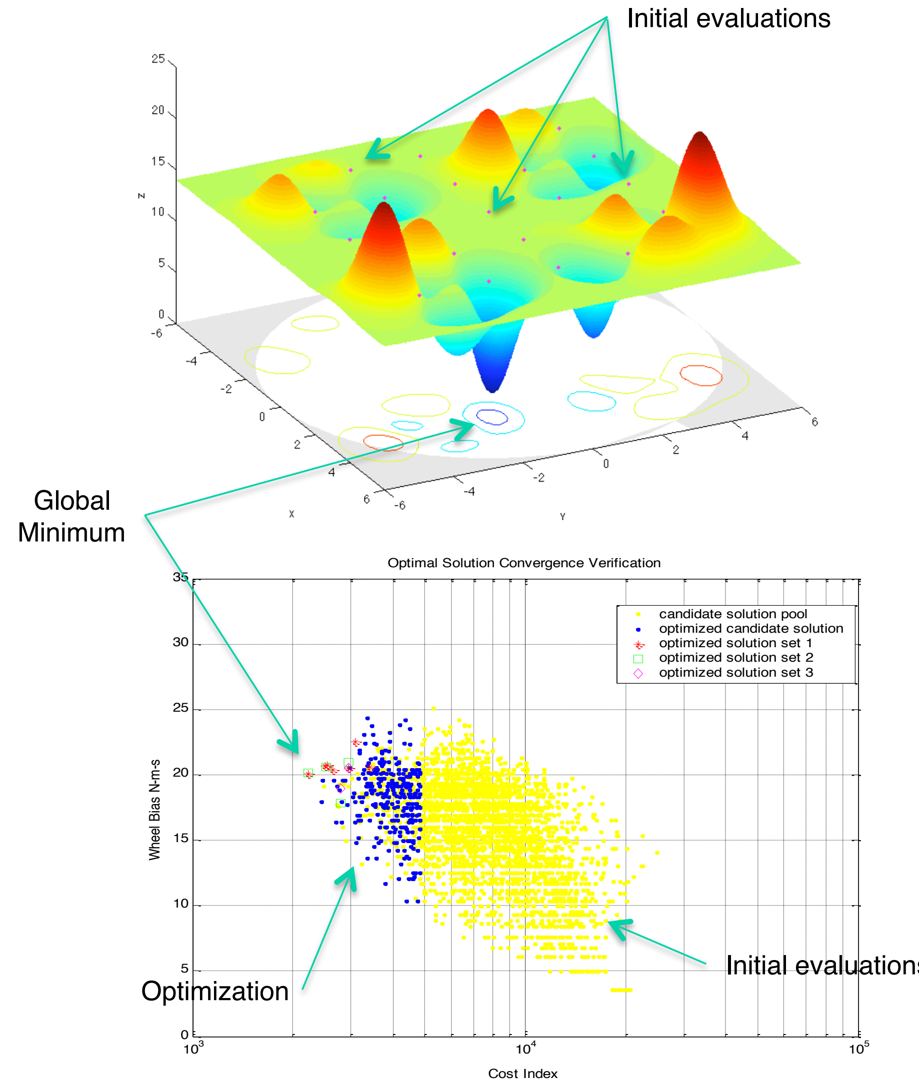
$$\vec{\omega}_{rwa} = [a]\vec{\omega}_{bias} + [b]$$

- Optimization cost functional as a function of input wheel bias

$$J(\omega_{bias}) = \sum_{i=rwa_{1,2,4}} K_i(|\omega_i|)$$

Find ω_{bias_opt} that minimizes $J(\omega_{bias})$

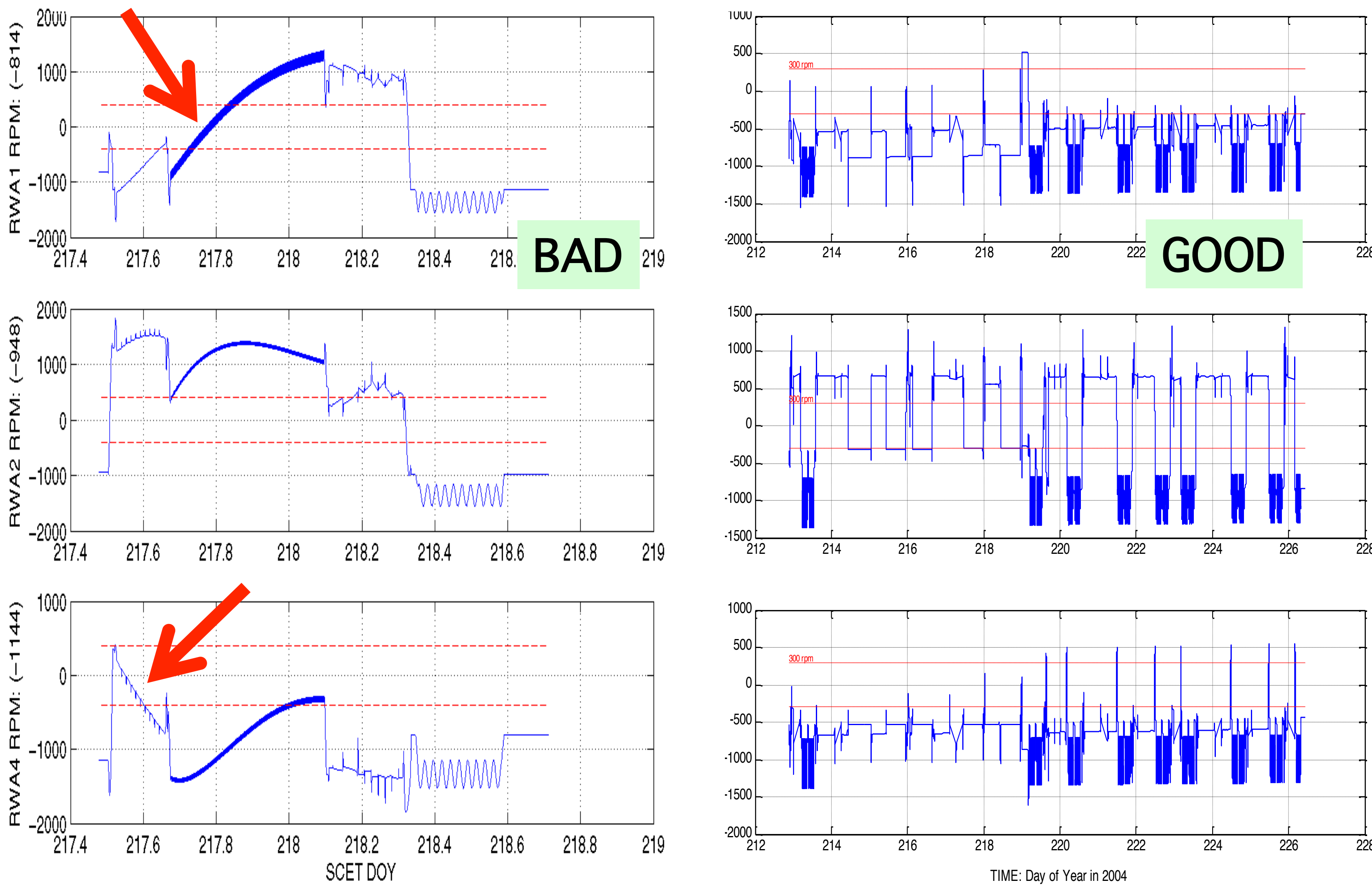
- Search for global minimum
  - Shotgun approach for initial evaluations
  - Select candidates for optimization to provide profile diversity
  - Perform optimization using Nelder-Mead Simplex method
  - Multiple optimizations to convergence



RBOT Key Operational Design Features

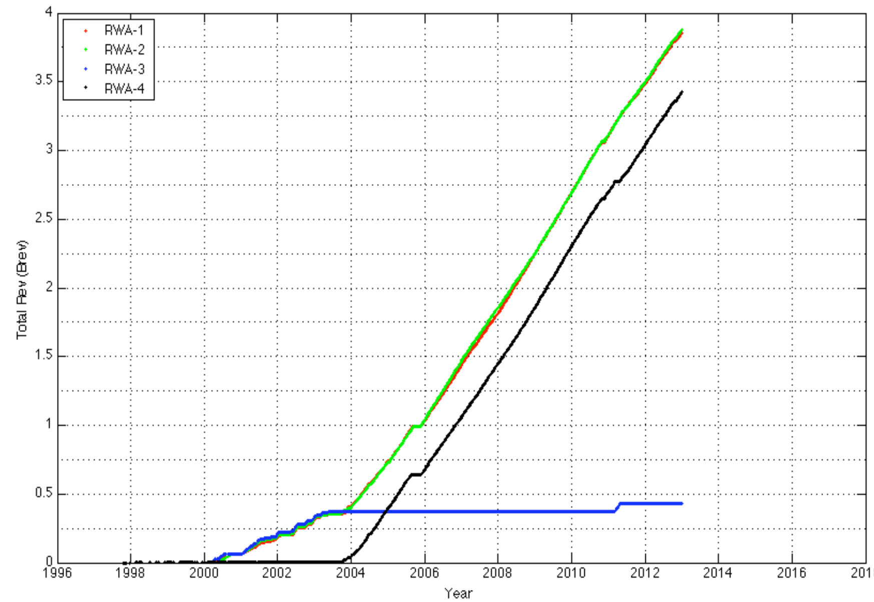
1. RBOT provide both optimal and sub-optimal solutions
   - Often time, the optimal solutions may not be the best choice. High value science often coincide with periods of undesirable RWA rate profile
   - Sub-optimal solutions provide users with alternatives in solving problematic time periods
2. Parallel processing capability
   - Improve computational efficiency by utilizing multiple workstations. Currently 9 CPUs are utilized
3. Bias Placement Optimization (BPO)
   - Automated placement of RWA biasing events. Eliminate the manual trial and error approach
4. Fuel Optimization (FO)
   - Generate fuel optimal solutions with minimal penalty to RWA health
5. Team work
   - Hold joint reviews with science planning and instrument teams to brainstorm RWA biasing problems and explore work-around solutions
   - RWA bias design activity integrated into Sequence Development Process

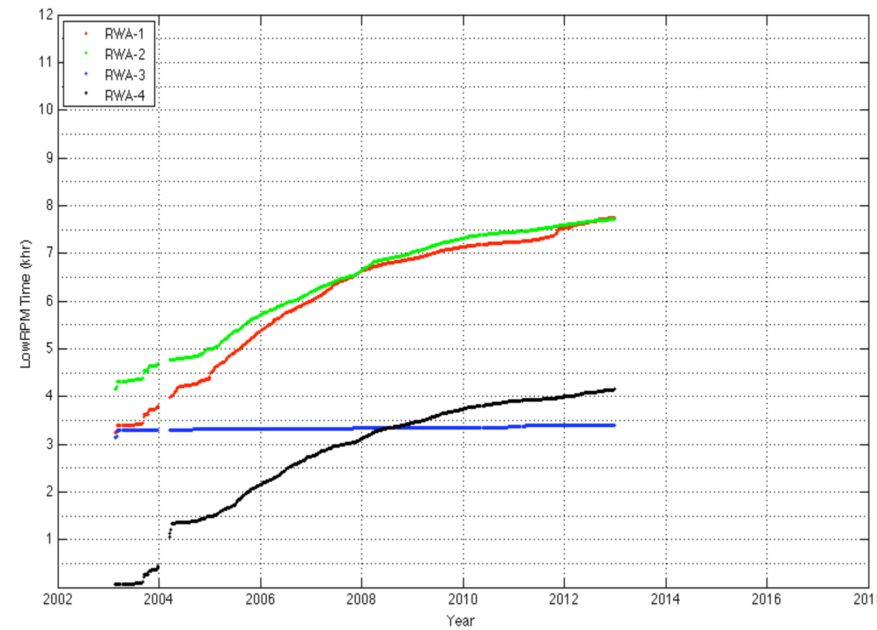
RWA-124 Rate Profile (Good and Bad Examples)



Status of Cassini RWA Consumables

- Pre-launch requirements of RWA consumables:
  - 4 Billions revolutions
  - 12 khr low-rpm (±300 rpm) time
- The consumption rates of the prime RWA revolutions in 2004–2013:
  - 1.14 million/day per wheel
- The per-wheel consumption rates of the prime RWA low-rpm time:
  - 2005–2006: 2.5 hr/day
  - 2010–2013: 21 min./day





RWA Operations Flight Lessons

1. Track RWA performance, beginning with wheel acceptance tests and throughout mission operations, to identify potential problems
2. Implement a RWA drag torque estimator in the flight software to provide ground visibility of any anomalous bearing drag conditions
3. Use a ground software tool (e.g., RBOT) to carefully manage RWA biasing events against prolonged low-rpm operations
4. Aggressively and constantly look out for opportunities in science observation sequence designs that can reduce low-rpm RWA operations
5. Ascertain that all the wheels' bearings are being maintained within the acceptable temperature ranges
6. If flight data indicates that the RWA lifespan may be constrained, use RWA to control S/C attitude only after the start of the prime mission
7. Review the FP design to identify its vulnerability when wheel drag torque is elevated. Should thresholds and/or persistence limits be changed?
8. Design, test, and exercise contingency procedures that will be needed to recover the S/C from a Safing state that is caused by a degraded/ failed RWA

Conclusion

Spacecraft attitude control reaction wheels must be managed with

Tender Loving Care